Physics at Very Large and Very Small Scales

Chu Ming-Chung 朱明中 MC^2
Department of Physics
The Chinese University of Hong Kong

Physics: Pushing the limits, from very large scales …

Not just in space, but also in time

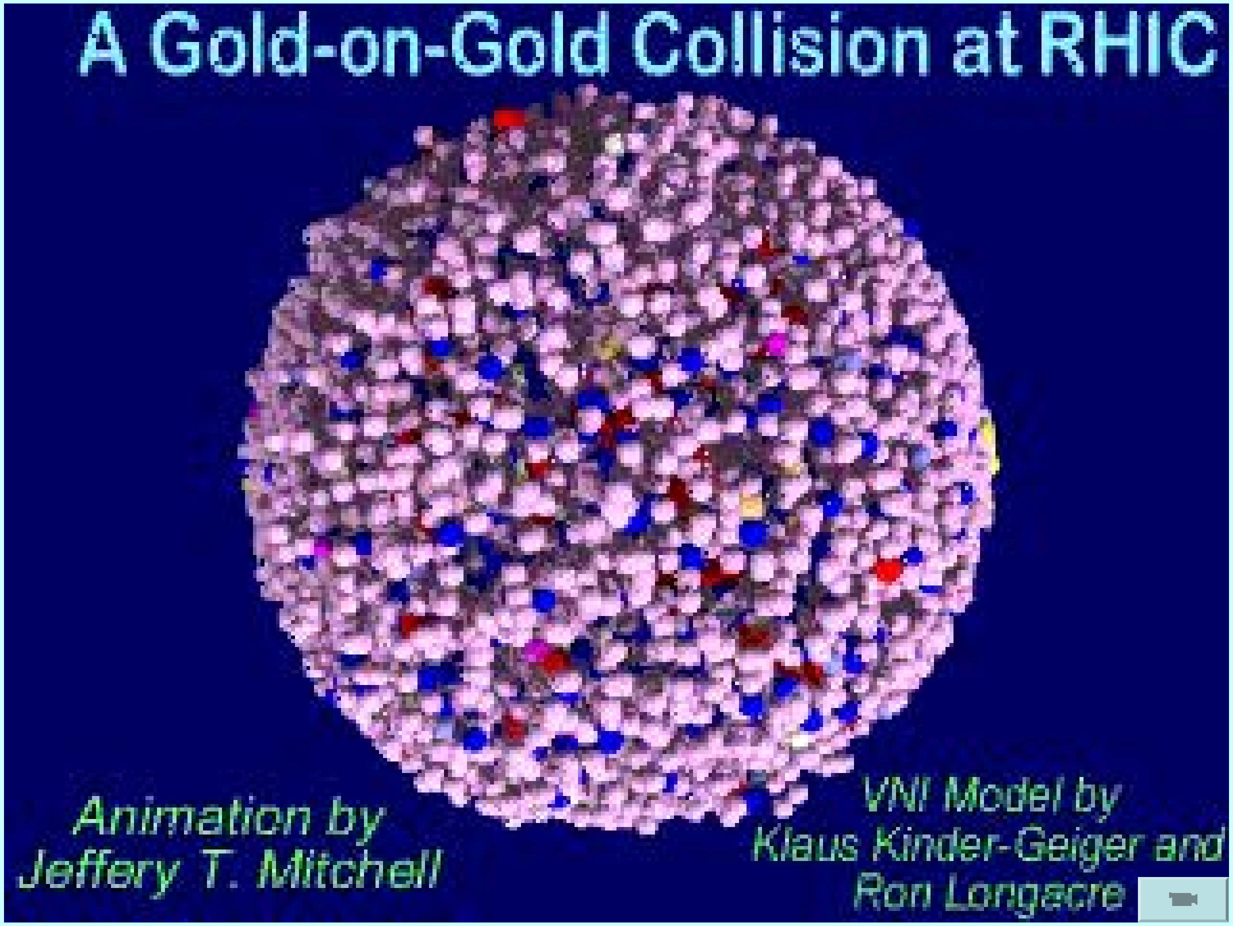
10^{10} light years, 10^{10} years

1 light year ~ 10^{16} m

Animation courtesy NASA/STScI

…, to very small scales.

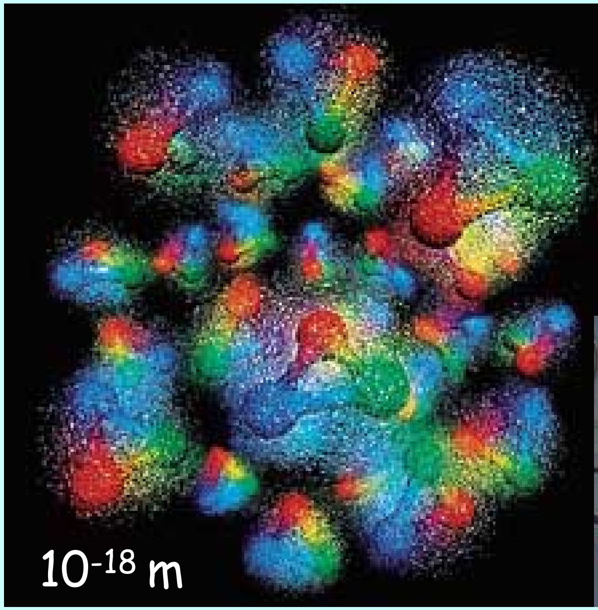
'sizes' of elementary particles < 10^{-18} m



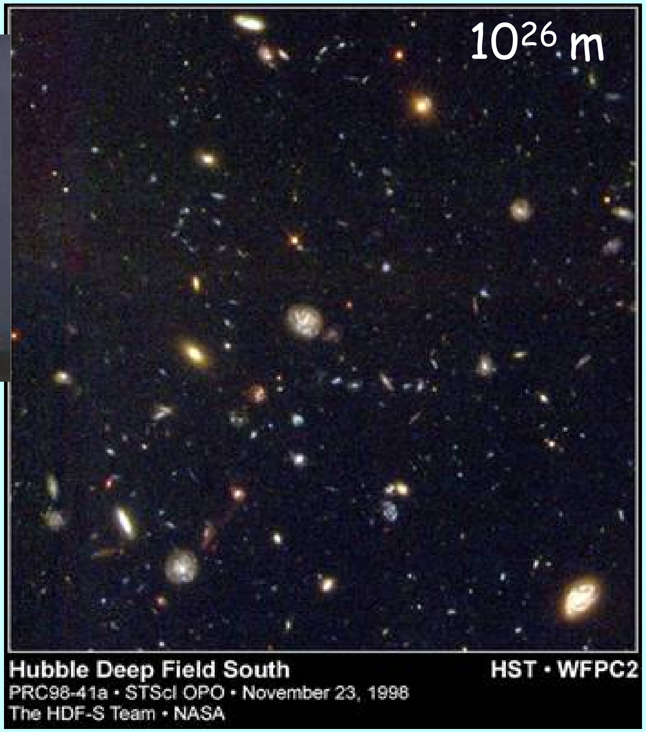
Collision of Au on Au at 200 GeV/nucleon
to make a fireball at $T \sim 10^{12}$ K

Particle Cosmology 粒子宇宙學

The physics governing the particle world is deeply connected to that governing the evolution of the universe: eg. how the fundamental forces are united determines the conditions at the early universe



Cartoon showing the quarks inside nucleons



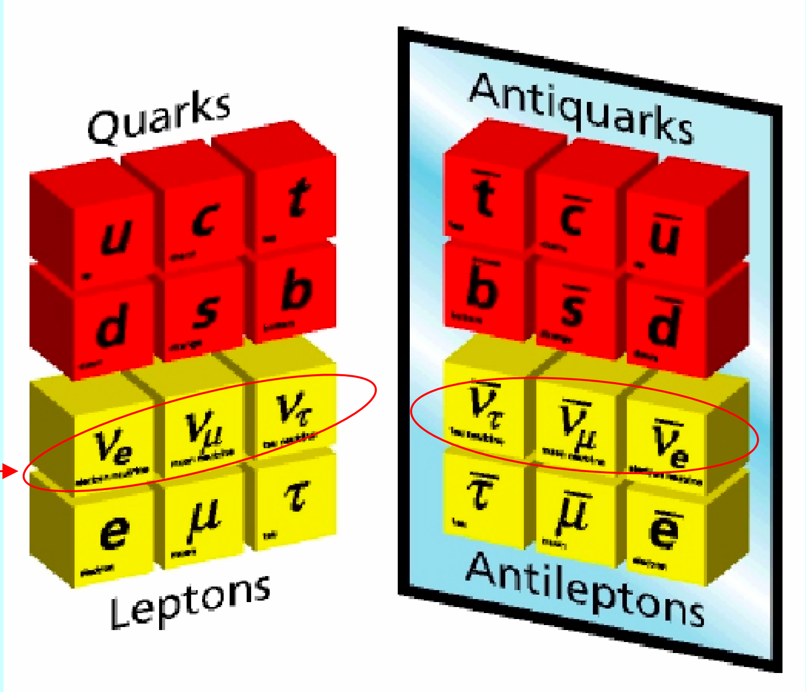
Deep space showing galaxies

Photo courtesy NASA/STScI

Standard Model of Particle Physics

- All matter are made up of quarks and leptons, which are elementary 基本粒子 (point-like, structureless)

Still have not understood these



- Interactions (strong, weak, EM, gravity) are characterized by a set of fundamental constants (forever and same value everywhere)
- There are 3+1 space-time dimensions

Some outstanding problems of our time

- What is the structure of space-time? How many dimensions are there?
- Are the 'fundamental constants' (eg. *G*, *e*, *c*, *h*,...) truly fundamental and constant in time? Over 10^{10} years?

  Cosmological answers to particle physics questions!

- What is dark energy?
- What is dark matter?
- Why are there so much more matter than anti-matter?
- ...

Particle physics answers to cosmological mysteries!

Physics at Very Large and Very Small Scales

- Some outstanding problems of our time
- Searching for extra dimensions from Cosmology
- Studying neutrino oscillations (θ_{13} in particular): Daya Bay Project
- Getting high energy particles for free: Aberdeen Tunnel Project

Are there extra dimensions?
(3+1+?)

Physics with Extra Dimensions

Generalize standard physics to (1+3+n) dimensions

Kaluza + Klein (1920's) – General Relativity in (1+3+1) dimensions → gravity + Maxwell Eq.

Extra dimensions could show up as effective forces!

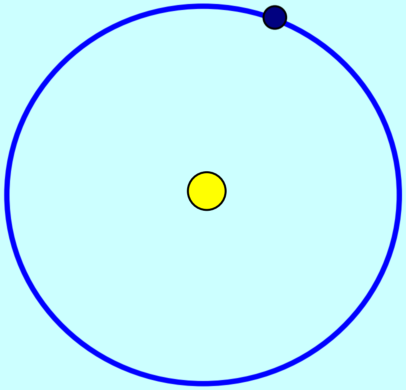
String theory (1990's) – the only self-consistent unified field theory so far, but consistent only for D =11, 26

Brane models (1990's) – our universe is in only one 4-d *brane* of the multi-dimensional universe

A Simple Example of Effective Force from Extra Dimensions

Imagine looking at the projected 1-D motion of a planet:

2-D



1-D

Circular motion:
gravity provides
centripetal force

$$F = -\frac{GMm}{r^2}$$

Simple Harmonic motion:
linear force!

$F = -kr$ Not ‘physical’ force!

extra forces → extra dimensions!

But we have not seen any sign of extra dimensions in laboratory. Could we be fooled by Earth's environment?

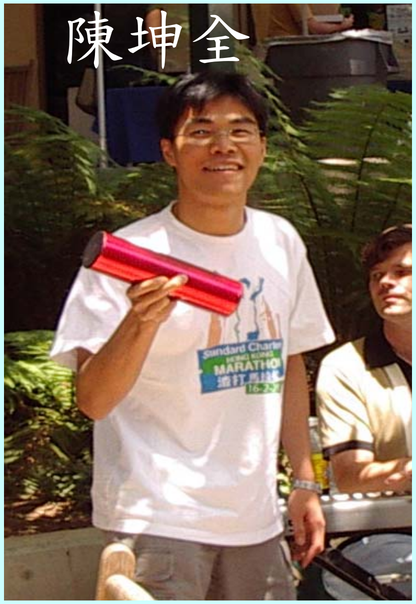
Could it be that we need to look at either very large or very small scales to see the extra dimensions?

Searching for extra dimensions in Cosmological signals!

Theory projects on signatures of extra dimensions

- Signatures in Cosmology? (Chan Kwan Chuen, Chan Wing Hang, Li Baojiu)
- Quantum Entanglement with Extra Dimensions (Ku Wai Lim)
- Particle motion in Brane models (Li King Fai)

Caltech



Cambridge

Extra-dimensional Cosmology

- Generalized General Relativistic Cosmology to include extra dimensions
- Study possible effects on observables
- Expansion history

Can explain accelerating expansion of universe (dark energy)

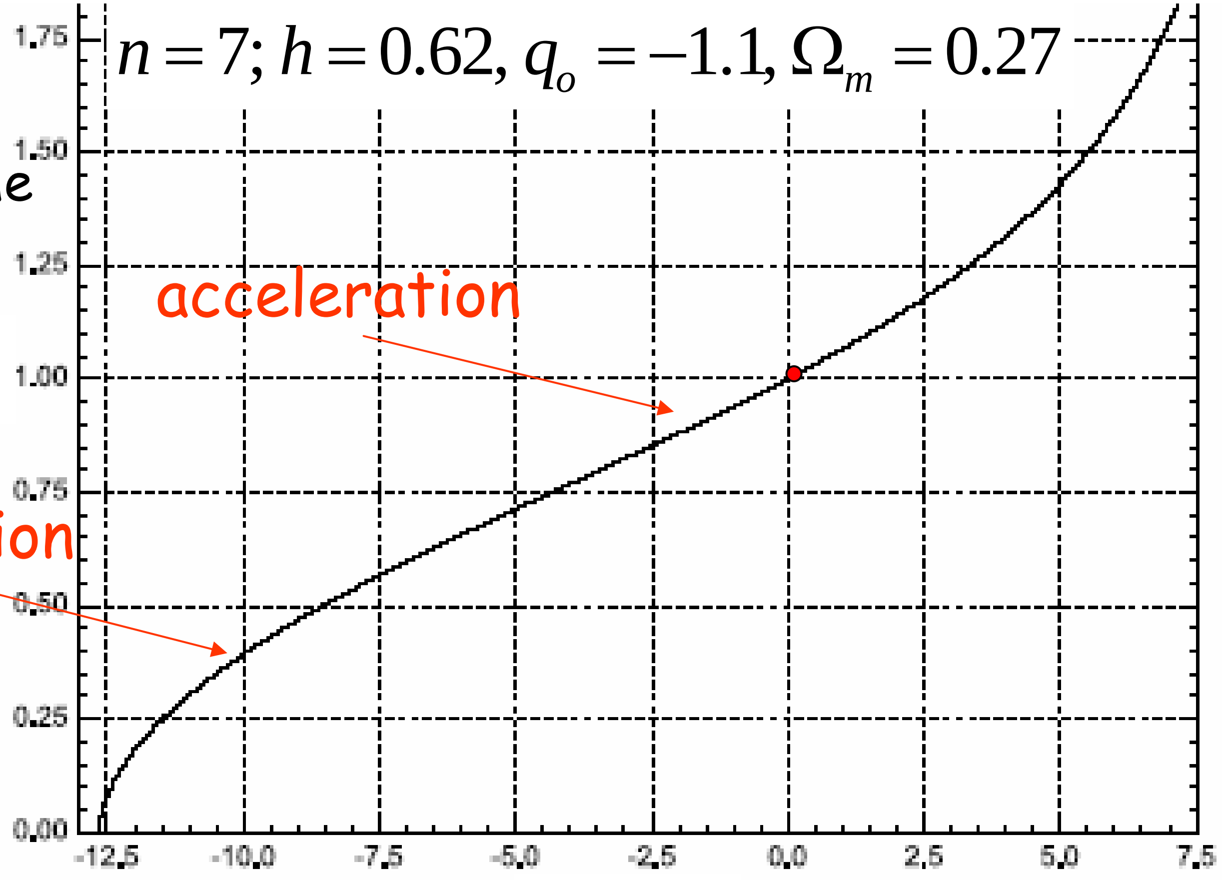
- Big Bang Nucleosynthesis (He, D, Li)
- Cosmic Microwave Background Anisotropies

Through varying fundamental constants

We are calculating how much the data allows the 'constants' to change $(e, h, G, c, m_e, m_p, \ldots)$

Evolution of the universe

Dark energy as a signature of extra dimensions (vacuum repulsion force = extra force)



$$n=7; h=0.62, q_o=-1.1, \Omega_m=0.27$$

Scale of the ordinary dimensions

a

acceleration

deceleration

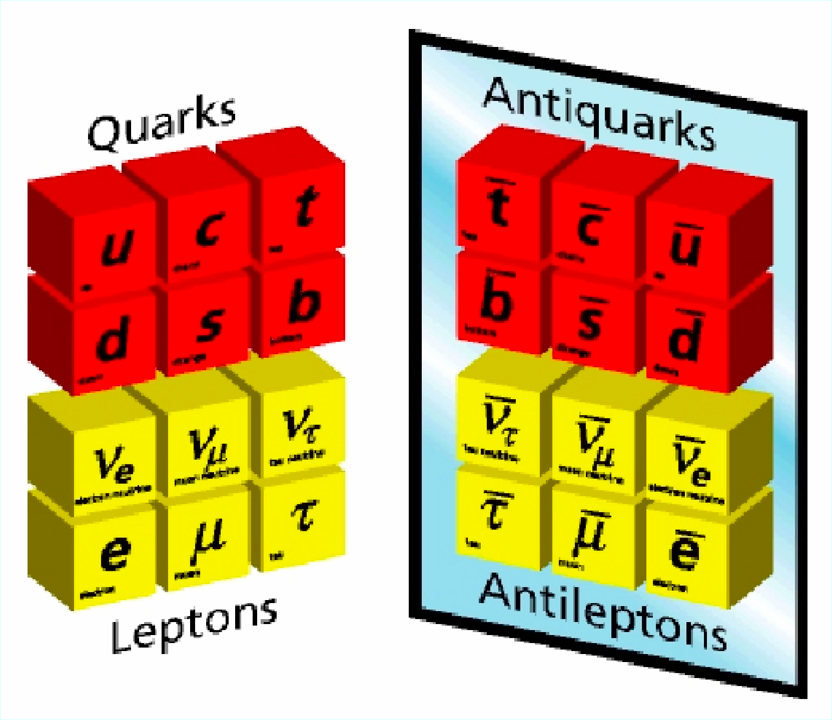
t (Gyr)

cosmic age ~ 13 GYr

today

Li *et al.*, CUHK Preprint, 2005.

Neutrino (中微子) Physics



Least understood particles

Neutrino 中微子

- Elementary particles (structureless, like electrons, photons, quarks)
- 3 kinds: $\nu_e \quad \nu_\mu \quad \nu_\tau$
- No electric charge
- Only interact via weak force (弱作用) and gravity (重力), no strong (強作用) or EM forces (電磁力)

  →strongly penetrating (eg. only 1 in 10^6 neutrinos from the sun interacts with the earth)
- Small rest mass $m_{\upsilon_e} < 1\mathrm{eV} \approx 10^{-6} m_e$

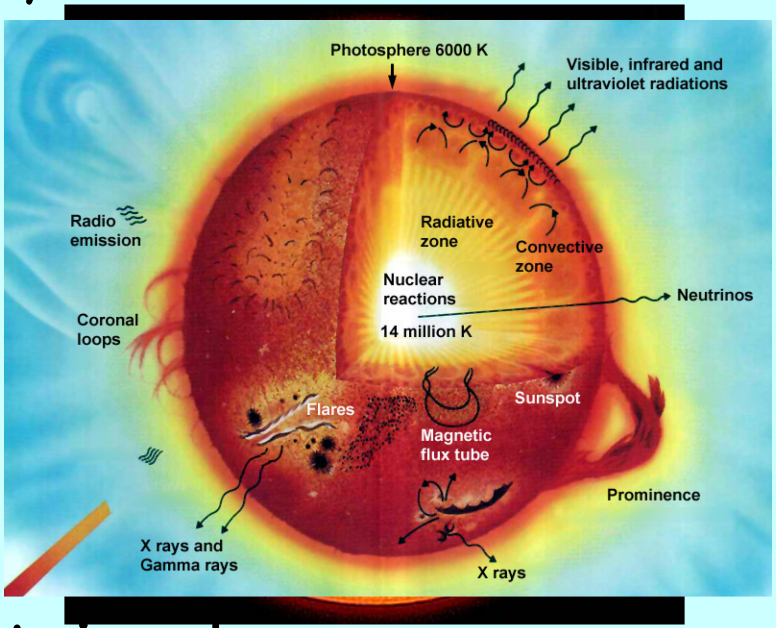
  http://www.ps.uci.edu/~superk/neutrino.html

  http://wwwlapp.in2p3.fr/neutrinos

Neutrino sources

- Neutrinos are emitted from hot and dense matter
- Eg. Nuclear fusion reactions, as in the sun:

$$4\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\upsilon_e + \gamma + 2e^{+}$$

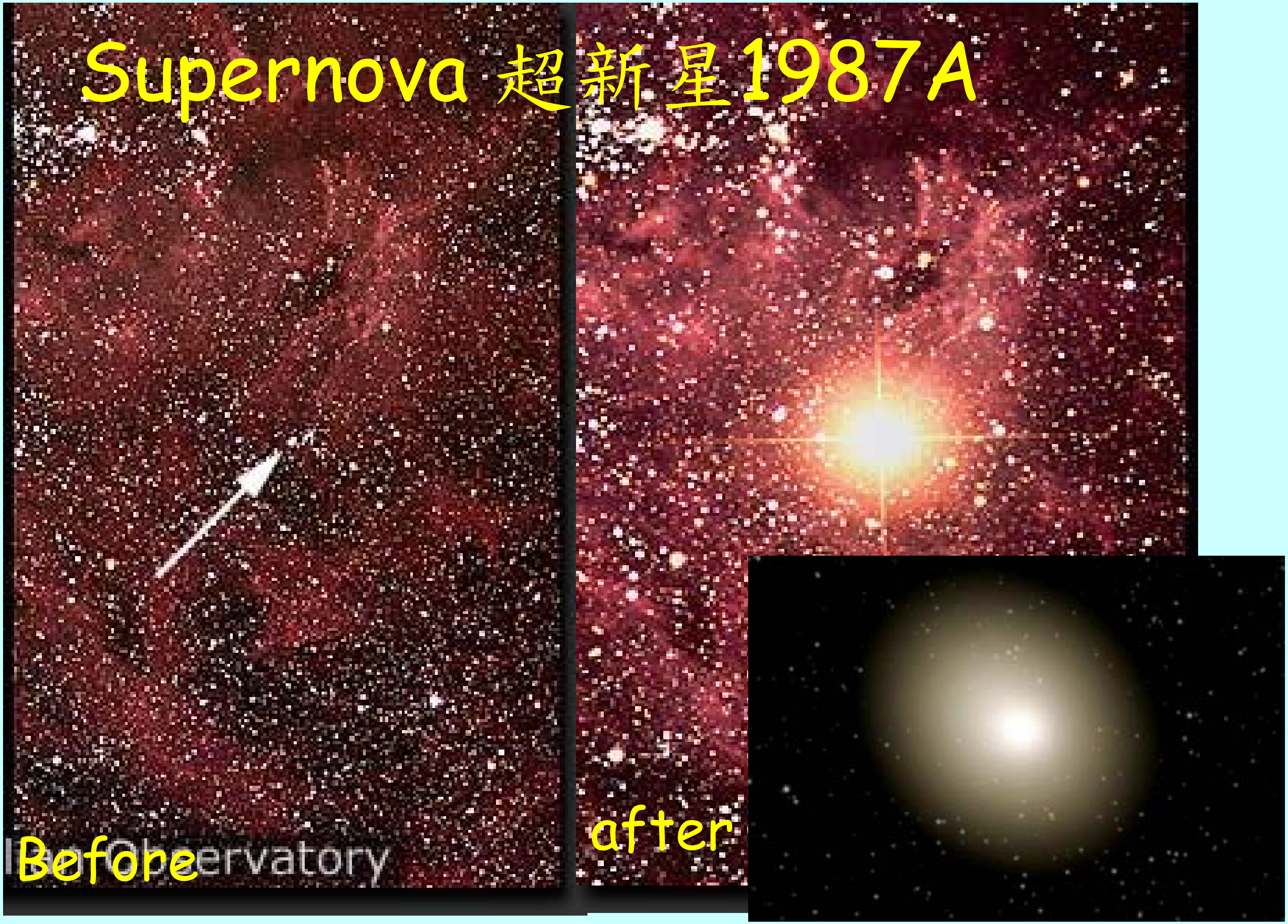


The sun emits $2 \times 10^{38}\ s^{-1}$ neutrinos!

Earth receives about $4 \times 10^{10}\ cm^{-2}\ s^{-1}$ neutrinos

http://wwwlapp.in2p3.fr/neutrinos

Supernova 超新星 1987A



Explosion of a dying massive star = huge source of neutrinos

Photo courtesy Anglo-Australian Observatory www.aao.gov.au/images/captions/aat050.html

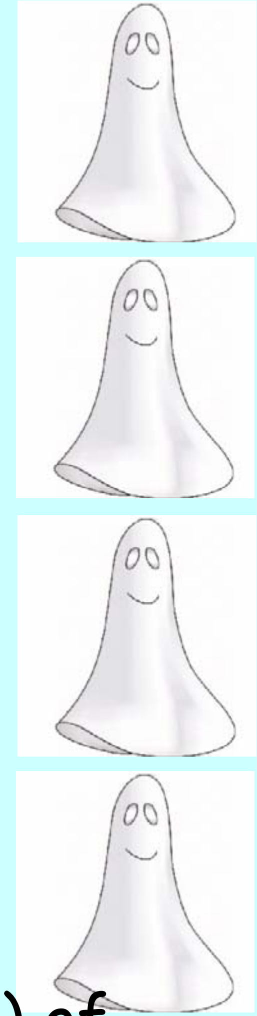
Neutrino Cosmology 中微子宇宙學

Big Bang: about 300/cc throughout the universe!

- Neutrino is a significant fraction of matter
- The number and mass of neutrinos affect structure formation in the universe
- CP violation in neutrino interactions may explain the matter-anti-matter asymmetry in the universe
- Neutrinos were emitted in the first second from the nuclear reactions in the primordial fireball → earliest signals possible, direct confirmation of Big Bang!

Neutrino Oscillation 中微子振蕩

Neutrinos can change from one type into another while propagating in space! (eg. $\nu_e \rightarrow \nu_\mu \rightarrow \nu_e$)



Solar Neutrino Problem: a large fraction (1/2 ~1/3) of neutrinos from the sun seems to disappear arriving at Earth!

A Proposal of Using the Daya Bay Nuclear Reactors For a Neutrino Experiment

To measure θ_{13} accurately!

Beijing Normal University, Brookhaven National Laboratory, California Institute of Technology, Charles University, China Institute of Atomic Energy, The Chinese University of Hong Kong, Illinois Institute of Technology, Institute of High Energy Physics, Iowa State University, Joint Institute for Nuclear Research, Kurchatov Institute, Lawrence Berkeley National Laboratory and University of California at Berkeley, Nanjing University, Nankai University, National Chiao-Tung University, National Taiwan University, National United University, Princeton University, Rensselaer Polytechnic Institute, Shenzhen University, Sun Yat-Sen (Zhongshan) University, Tsinghua University, University of California at Los Angeles, University of Hong Kong, University of Houston, University of Illinois at Urbana-Champaign, University of Wisconsin, Virginia Tech University

28 institutes from mainland China, Hong Kong, Taiwan, USA, Czech Republic, and Russia

大亞灣 Daya Bay (China)

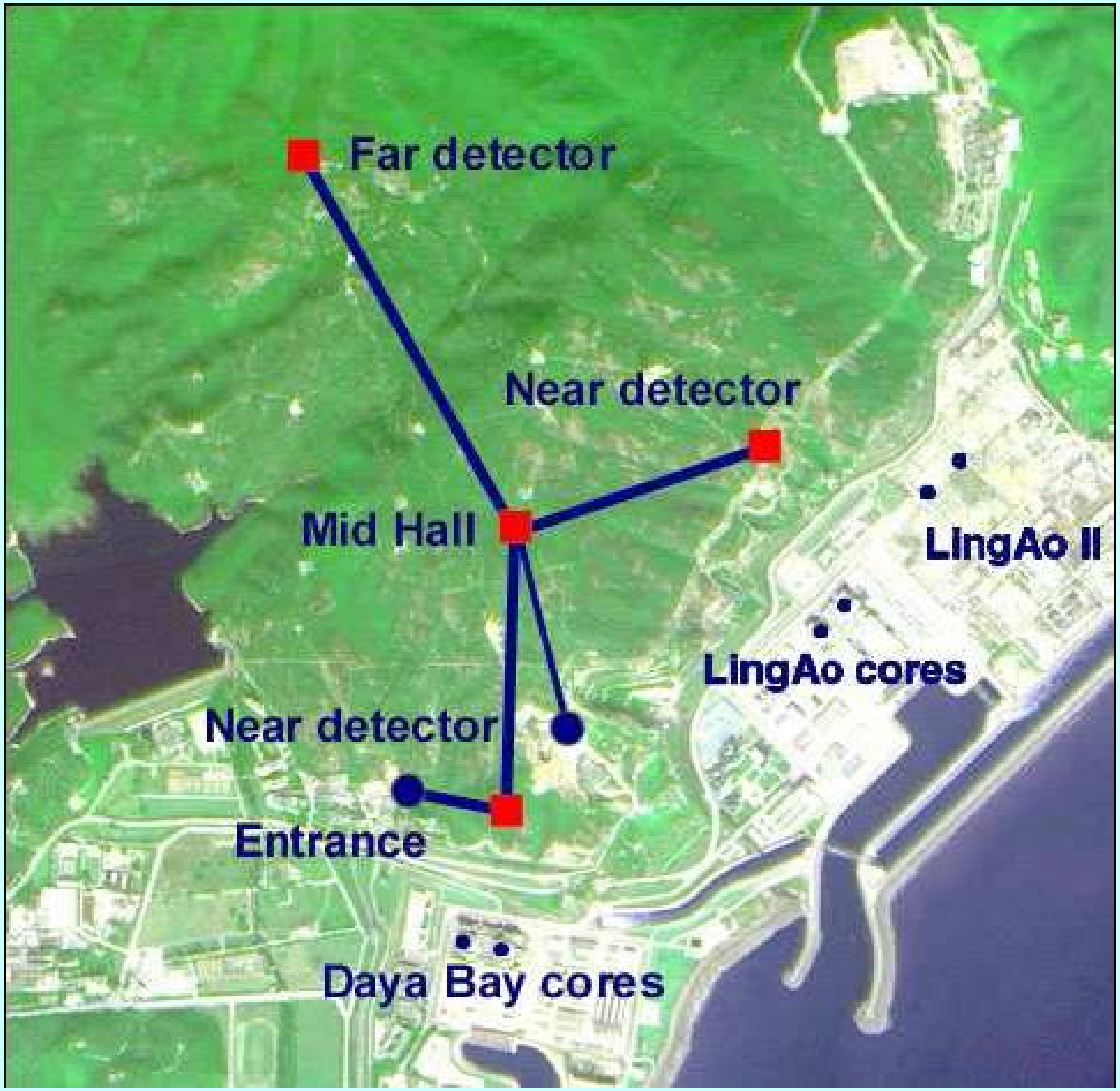
2+2(+2) reactors: 11.6 (17.4) $\mathrm{GW_{th}}$

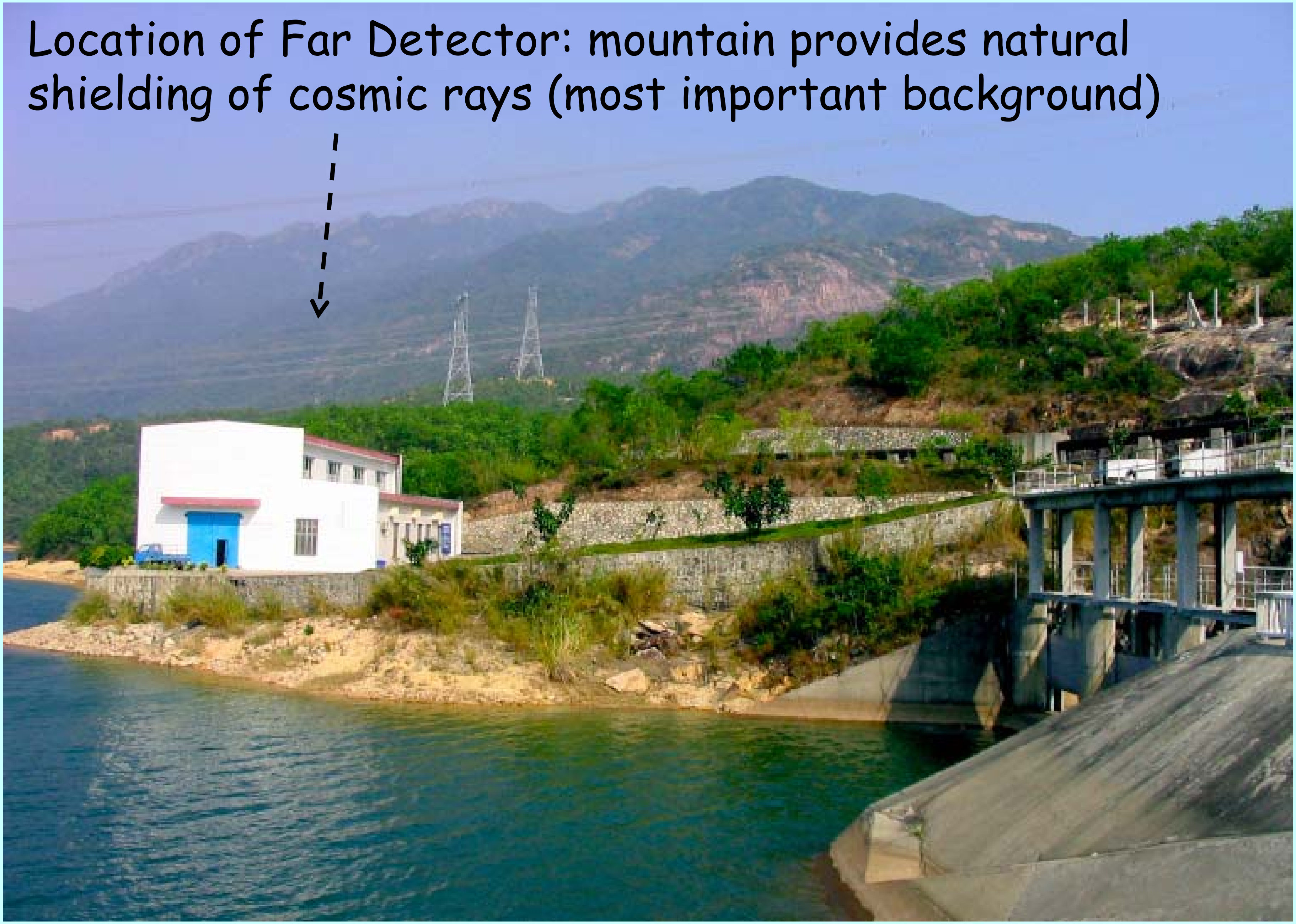
High power + high mountains

About 10^{20} anti-neutrinos s^{-1} from a 1 GW nuclear power plant

Daya Bay Nuclear Power Plant

Layout of the Daya Bay Experiment





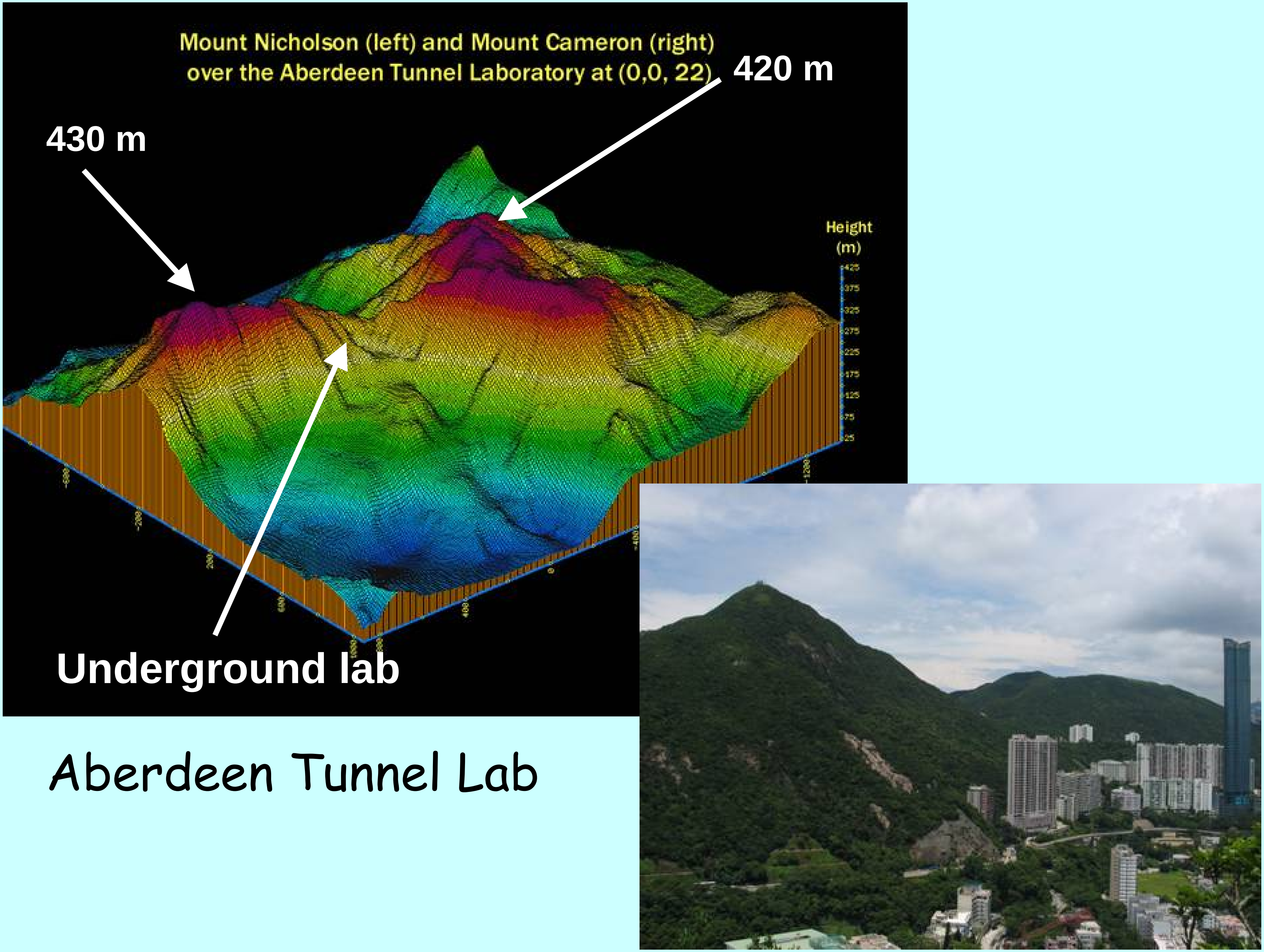
Location of Far Detector: mountain provides natural shielding of cosmic rays (most important background)

Studying cosmic muons at Aberdeen Tunnel

A satellite lab of Daya Bay Experiment – to study the most important background

Brookhaven National Laboratory
The Chinese University of Hong Kong
Institute of High Energy Physics, CAS 中科院高能所
Lawrence Berkeley National Laboratory and U. C. Berkeley
National Chiao-Tung University 台灣交通大學
National Taiwan University 台灣大學
National United University台灣聯合大學
The University of Hong Kong

http://theta13.phy.cuhk.edu.hk/



Aberdeen Tunnel Lab

Studying Background in Aberdeen Tunnel Laboratory

Over 20 students from CUHK have been involved!

Antony

Joseph

傻番梘

→ UIUC

A team in China and others around the globe hope an obscure property of neutrinos may answer the question of why the universe isn't full of antimatter

HONG KONG—It's nearly 1:30 a.m. when three unmarked cars ease into a deserted tunnel linking Hong Kong's central business district and Aberdeen, a residential community in the island's southwest corner. About halfway through the mountain passage, which is closed for maintenance, the cavalcade rolls to a halt beside a cavernous service hall. A young man leaps out and unlocks a steel door, and his colleagues swarm into a tiny, humid room hewn from granite. After a couple of hours of fiddling with electronics and scintillation counters, the group huddles around a computer. "We have a signal," says a young physicist, beaming with pride.

This is Soap!

傻番梘

Science Magazine VOL. **313**, p. 291, 21 JULY 2006

NEWSFOCUS

uclear to
cit

A team in China and others around the globe hope an obscure property of neutrinos may answer the question of why the universe isn't full of antimatter

HONG KONG—It's nearly 1:30 a.m. when three unmarked cars ease into a deserted tunnel linking Hong Kong's central business district and Aberdeen, a residential community in the island's southwest corner. About halfway through the mountain passage, which is closed for maintenance, the cavalcade rolls to a halt beside a cavernous service hall. A young man leaps out and unlocks a steel door, and his colleagues swarm into a tiny, humid room hewn from granite. After a couple of hours of fiddling with electronics and scintillation counters, the group huddles around a computer. "We have a signal," says a young physicist, beaming with pride.

This is no spy operation. The physicists in the Aberdeen Tunnel are testing their scintillation counters by spotting muons, particles produced when cosmic rays slam into the upper atmosphere. The setup is a prelude to an ambitious attempt to slay one of physics's most obdurate dragons: Why is there so much more matter than antimatter in the universe? Construction is planned to begin in 2007 on the main attraction 55 kilometers northeast on the mainland: the Daya Bay Neutrino Experiment—a set of detectors up close and personal with a nuclear power plant. Last month, the Chinese government pledged $6.25 million to the effort.

Daya Bay and four similar efforts worldwide are vying to measure a fundamental property of neutrinos, ghostly particles that rarely interact with normal matter. Only in the past decade have physicists confirmed that neutrinos have mass, albeit minuscule, and oscillate between three flavors: electron, muon, and tau neutrinos. Physicists have enumerated four measurable oscillation properties: three "mixing angles" and the charge-conjugate parity (CP) value. Two angles are known from studies of neutrinos from the sun, the atmosphere, reactors, and accelerators. Only an upper limit has been reached for the third mixing angle, θ_{13}, while the CP value remains an enigma.

CP is of supreme significance: If neutrinos violate CP, that could explain why antimatter is now so scarce. Quarks are proven CP violators, but that's "not enough" to explain the matter-antimatter imbalance, says Ming-Chung Chu, a theoretical physicist at the Chinese University of Hong Kong. "CP violation in neutrinos is what we really need to go after," adds physicist Kam-Biu Luk of the University of California, Berkeley, and Lawrence Berkeley National Laboratory. The only way to solve the riddle is to first measure θ_{13}.

Enter Daya Bay and its brethren. They will use nuclear power plants to study θ_{13}. The nuclear chain reaction produces a flood of electron antineutrinos, which are assumed to have the same fundamental properties as neutrinos. All five experiments will install a detector near a reactor to measure antineutrino flux and then place an identical detector a certain distance away. The few antineutrinos that might oscillate as they travel that distance will evade the second detector because it can register only electron antineutrinos. This dip in antineutrino flux would yield θ_{13}. Most theorists believe that the target value—$\sin^2 2\theta_{13}$—lies between its present limit of 0.19 and 0.01, says Maury Goodman, a neutrino physicist at Argonne National Laboratory in Illinois.

Physicists need as large a supply of antineutrinos as possible, because few will actually interact with the detectors, and even fewer will oscillate and show up as a deficit. The detectors must be shielded from background radiation that can mimic the antineutrino signature. The teams plan to cocoon their detectors—in all five cases, massive tanks filled with a gadolinium-doped scintillator solution—inside a mountain or in an underground shaft and sheathe them in water or metal to absorb particles other than antineutrinos. However, cosmic-ray muons can barrel through these defenses. And that's why Aberdeen Tunnel is a good warm-up: Physicists hope to learn how to differentiate between the flashes caused by muons and antineutrinos.

Daya Bay won't be the first out of the gate. The French-led Double Chooz group aims to start taking data next year. Nor will Daya Bay have access to the biggest antineutrino source: The Japanese KASKA team intends to track the particles from the world's most powerful assemblage of reactors, the Kashiwazaki Kariwa Nuclear Power Plant near Niigata. "It's a healthy competition," says KASKA physicist Fumihiko Suekane of Tohoku University. But thanks in part to favorable positions right up close to the Daya Bay Nuclear Power Plant and its neighboring Ling Ao plant, the Daya Bay experiment is poised to be the first to reach the 0.01 benchmark within 3 years of start-up.

Whether that will be good enough to snare θ_{13} is an open question. "It's unknown exactly how sensitive these experiments will be," cautions Goodman, the U.S. co-spokesperson for Double Chooz. He says that initial measurements "will be steps along the way to more precise experiments."

The Daya Bay collaboration is headed by Luk and Wang Yifang of the Institute of High Energy Physics in Beijing, who have assembled a 100-strong team from 24 institutions in four countries. The group has cash in hand from the Chinese Academy of Sciences, and commitments are expected this fall from China's Ministry of Science and Technology and other agencies. The U.S. Department of Energy is also backing Daya Bay with $800,000 for R&D this year and is expected to add more. "It's groundbreaking for us. Hong Kong has never been involved in a physics project of this kind," says Chun-Shing Jason Pun of the University of Hong Kong. And it is strengthening scientific links across the Taiwan Strait, with three Taiwanese and seven mainland institutions taking part.

There's always a chance that the predictions are wrong and that the θ_{13} value will be much smaller than 0.01, perhaps even 0—and frustratingly out of reach. That would leave experimentalists and theoreticians alike scratching their heads. Chu, for one, is not perturbed by that prospect. "That would mean new physics," he says. "Either way, we can't lose."

—RICHARD STONE

Limbering up. Kam-Biu Luk examines a scintillation counter in the Aberdeen Tunnel.

The Race for θ_{13}

Project	Location	Present power (gigawatts)	Start-up (projected)	Maximum sensitivity*
Angra	Brazil	6	2013	0.007
Daya Bay	China	11.6	2010	0.008
Double Chooz	France	8.2	2007	0.02
KASKA	Japan	24.3	2009	0.015
RENO	South Korea	17.3	2009	0.02

*$\sin^2 2\theta_{13}$

Source: Kam-Biu Luk; Maury Goodman/Argonne National Laboratory; Fumihiko Suekane; Institut National de Physique Nucléaire et de Physique des Particules

PHOTO CREDIT: R. STONE/SCIENCE

www.sciencemag.org SCIENCE VOL 313 21 JULY 2006 291

Published by AAAS

Objectives

- To measure muon flux, angular distribution at ~ 250 m rocks (with similar compositions as Daya Bay)
- To compare with muon simulations and calibrate software – useful for all underground experiments, such as dark matter search
- To study muon-induced neutron background (next phase)
- To train students and research personnel

Physics at Very Large and Very Small Scales

- Some outstanding problems of our time
- Searching for extra dimensions from Cosmology
- Studying neutrino oscillations (θ_{13} in particular): Daya Bay Project
- Getting high energy particles for free: Aberdeen Tunnel Project

Physics at Very Large and Very Small Scales

Chu Ming-Chung 朱明中 MC^2

Department of Physics

The Chinese University of Hong Kong